A rotary screw conveyor is to be designed to discharge Willow wood chips from the below ground bin illustrated, at a suitable rate of X tonnes per hour, into the furnace. The conveyor is a Y m long inclined screw conveyor which elevates the material 5 m. You may try a standard pitch screw selected from one of the standard diameters given in the tables. Consider also alternatives which may be preferable. Why? The equipment is in a covered area.

Preliminaries:

Read the attached article “Energy from Willow” and make your estimates of X and Y based on data in the paper.

Determine:

(i) The required screw diameter (mm),
(ii) The required screw speed (rpm),
(iii) The power required at the drive shaft (kW),
(iv) The maximum length this conveyor could be without exceeding the torsional ratings of standard pipe, shaft and coupling bolts listed in Table 2.4 – Torsional Ratings of Screw Conveyor.
(v) What special problems (list at least three) should be anticipated with this system?
(vi) How should the special problems of (v) be combated?

2. What secondary equipment will be needed? For example: How should the machines be fed? What equipment will be suitable at the entry of each machine? How will the material enter the furnace? Any special equipment? Carefully read the paper and perform any extra research that you consider to be necessary to assess the requirements for extra equipment directly associated with the screw conveyor. Is the dump hopper suitably shaped? Suggest alternative shape(s)

3. What other equipment may be used to perform the function of the screw conveyor?

4. Tabulate and compare all relevant parameters for two methods of lifting this material into the furnace?

5. Submit your answers as a summary report, comparing the two systems. Illustrate with sketches. Discuss all factors in your comparison of the two methods above: Costs (capital and running); Size; Convenience; Environment; Access; Maintenance. Attach references and relevant websites with your submission.

Energy from Willow
Energy from Willow

This booklet has been written to give an overview of energy production from willow. Most of the text is drawn from experience in Sweden, UK and the Netherlands, but the information will be applicable in other parts of the world.

It was produced as part of the REGROW project undertaken jointly by:

- SAC The Scottish Agricultural College, Edinburgh, United Kingdom
- SLU Swedish University of Agricultural Sciences, Uppsala, Sweden
- ECN Netherlands Energy Research Foundation, Petten, Netherlands

The project was carried out under contract as part of the ALTENER II programme of the European Commission. The work by SAC was supported by the UK Department of Trade and Industry’s (DTI’s) New & Renewable Energy Programme, which is managed by ETSU on behalf of the DTI. The Netherlands Agency for Energy and Environment (Novem) provided additional support for work carried out at ECN. The views and judgements expressed are those of the contractors and do not necessarily reflect those of the European Commission, Novem, ETSU or the DTI.

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Compiled by:  
- **John Boyd** (SAC)  
- **Lars Christersson** (SLU)  
- **Ludger Dinkelbach** (ECN)

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1 Introduction

Willow can produce large quantities of renewable "green" energy without harming the environment. Growing willow for energy contributes to sustainable development in rural communities. Willow yields a fuel that can be stored until needed, and then used to generate heat and electricity.

Willows offers great potential as a source of renewable energy, that does not add to production of greenhouse gases or acid rain.

Producing willow as an energy crop contributes to sustainable development:
- putting the land, and the farmers' skills and equipment, to good use;
- securing jobs in rural areas;
- helping rural communities to remain viable.

Willow grows throughout the northern hemisphere, mainly in cold and wet areas, and a few species are native to the southern hemisphere. Willows:
- produce a lot of biomass in a short period, and are among the fastest growing woody species in northern Europe;
- can be grown with low inputs of agro-chemicals;
- are easily established from un-rooted cuttings;
- re-sprout vigorously after each harvest;
- offer large potential for genetic improvement;
- have an energy balance in the region of 20:1 (i.e. the energy obtained can be 20 times as much as the energy used to grow the crop);
- can be used as a vegetation filter during "bio-remediation" of waste water or contaminated land.

Willow grows very quickly in favourable conditions.
Willow for energy is normally grown as coppice. The plants are cut back at intervals near ground level, and allowed to re-grow as multiple shoots (a coppice “stool”) rather than a single stem. Willow coppice might be harvested up to six times, typically at intervals of 3 - 5 years. At the end of that time (perhaps 25 years), the stumps can be removed, and the land re-planted with agricultural crops or more coppice.

Willow can be used to produce heat or electricity. Electricity is either used on site, or sold through a distribution grid. An engine or turbine driving a generator converts only 25 - 33% of the energy content of the fuel into electricity, the remainder is emitted as heat. Where this heat energy can be utilised in a combined-heat-and-power (CHP) system, the total efficiency can be increased to 85% or more.

There are three methods for converting willow into energy:
- **combustion** is used for heating water or to raise steam for a turbine;
- **gasification** produces a combustible gas that can be burned in a boiler, or used as fuel for an engine or gas turbine;
- **pyrolysis** can be used to convert the crop into gas, oil or charcoal fuels.

One hectare of a well-managed willow plantation can yield 10 - 12 tonnes of dry matter per year, with energy equivalent to about 5 000 litres of oil.

As a rough guide, 1 kg of willow will yield about 1 kWh of electrical output. A district heating scheme for a development of 100 houses would require about 25 hectares of willow coppice. A combined heat and power system with 100 kW electrical output will use 50 ha of willow coppice harvested on a three year cycle. A power station generating 5 MW of electricity would need around 2 500 ha of willow.

Most users need chipped fuel. The chipping operation, sometimes referred to as "comminution", often takes place during harvesting. Alternatively the crop can be harvested as long sticks, and chipped later.

Willow is harvested in winter. This coincides with the main demand for space heating, but electricity and industrial process heat are generally required all year round. Storage requirement can be minimised by using willow as it is harvested during winter, and other fuels (usually forestry residue) over the remainder of the year.

Storage and transport need careful management. Freshly harvested chips can deteriorate in store unless they are dried; full length willow sticks are easier to store, but more difficult to transport.
Why coppice?

Some plants accumulate a lot of dry matter in their roots, others in leaves and stems (where it can be harvested repeatedly in a coppice system). Willows tend to have a shallow and sparsely spread rooting system in the early years, but allocate more dry matter to the roots in later years. Harvesting at 3 - 5 year intervals ensures that the vigorously growing juvenile stages are maintained, and dry matter continues to accumulate in the stems.

Growing willow together with other trees

In Sweden, willows and poplar have been grown in mixed stands with deciduous or coniferous trees. Alder species are able to fix atmospheric nitrogen, and in a mixed stand the willow may need less fertiliser than in a pure stand. Spruce seedlings grow very slowly and prefer shade in the early years, and are not ready for harvesting until 25 - 50 years after planting. A combination of spruce and willow can be planted side by side, with one row of spruce and two rows of willow. The willow can be harvested 3 - 4 times before the spruce takes over the land area.

UNITs commonly used in the biomass energy industry

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Conversion</th>
<th>Notes</th>
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<tbody>
<tr>
<td>kW</td>
<td>kilowatt unit of power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MW</td>
<td>megawatt unit of power</td>
<td>= 1000 kilowatts</td>
<td></td>
</tr>
<tr>
<td>kWh</td>
<td>kilowatt hour unit of energy</td>
<td>equivalent to 1 kW for 1 hour</td>
<td></td>
</tr>
<tr>
<td>MWh</td>
<td>megawatt hour unit of energy</td>
<td>= 1000 kWh</td>
<td></td>
</tr>
<tr>
<td>MJ</td>
<td>megajoule unit of energy</td>
<td>= 0.277 kWh</td>
<td>often used in relation to gas, oil or solid fuels</td>
</tr>
<tr>
<td>kJ</td>
<td>kilojoule unit of energy</td>
<td>= 0.001 MJ</td>
<td></td>
</tr>
<tr>
<td>kW_e</td>
<td>kilowatt electrical</td>
<td></td>
<td>used to distinguish between types of energy output, particularly for combined-heat-and-power systems</td>
</tr>
<tr>
<td>MW_e</td>
<td>megawatt electrical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kW_th</td>
<td>kilowatt thermal</td>
<td></td>
<td>used in the wood fuel industry</td>
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<tr>
<td>MW_th</td>
<td>megawatt thermal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>odt</td>
<td>oven dry tonne mass of dry matter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gt</td>
<td>green tonne mass of fresh material</td>
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2 Case studies

Installations described here range from a heating system for a school, up to power stations serving many thousands of households.

Brook Hall Estate, Londonderry, Northern Ireland

Brook Hall Estate has demonstrated how willow for energy can be integrated into a commercial farming system.

Heat and electricity were initially produced from forestry residues, while the willow coppice was being established. Now that mature willow is available, 14 ha are cut and chipped each year using a tractor-mounted harvester, and transported using farm trailers.

The willow chips are dried on an existing ventilated floor grain drier, and transferred to a gasifier. A conventional diesel engine runs on the gas (together with a small percentage of diesel) and drives a generator producing 100 kW of electricity, which is sold to the local power utility. Waste heat from the engine cooling system and exhaust are used to heat houses on the estate, and for drying both willow chips and grain.

Proven technology has been used wherever possible. The gasifier is filled once a day using an agricultural telescopic handler, avoiding the need for any complex biomass conveying equipment. The engine and generator are standard industrial models, and additional trials are being carried out using a small gas turbine. Willow production complements the other farm enterprises, employing labour and machinery during winter, and using the drying floor after the grain harvest is finished.

Electricity is sold under Northern Ireland’s Non Fossil Fuel Obligation arrangements. Under this scheme, the UK government invites companies to bid for a long term contract to generate energy from renewable sources, and the price is enhanced to encourage development of new technologies.

The willow to energy system adopted at Brook Hall Estate is one that could be replicated on many farms and a new company, Rural Generation Ltd, has been formed to market the technology.
Lelystad, Flevoland, Netherlands

The power company Nuon recently commissioned a combined-heat-and-power combustion plant in Lelystad. The grate burner and steam turbine supply 1.3 MW of electricity to the grid, and 6.5 MW of thermal energy to the town's central heating system, with a total efficiency of 85%. The fuel, wood from conventional forestry thinnings as well as residues from landscape plantings, urban parks and gardens, is collected within a radius of about 40 km. From the year 2002/2003 on, dedicated energy crops will be used up to a maximum of 10% of the total fuel input.

The first plantings (15 ha) were carried out in 1999 and another 35 ha, mainly willow and poplar, were planted in 2000. In the longer term, the total area of energy plantation will amount to 200 ha. In this project the short rotation crops will be combined with other forms of land use, to create an attractive landscape that is both profitable and socially acceptable. The project is a joint activity of a series of companies and institutions including the Dutch government, the province of Flevoland, the utility company Nuon, research centres and environmental organisations.

Support for renewable energy projects in the Netherlands is available through various measures, including low-interest loans from “Green Funds”. Savers in the Green Funds do not pay income tax on the interest received. Accelerated depreciation is permitted for equipment on an approved list. Consumers pay an energy tax, which is collected by the utilities and passed on to the generators of renewable energy. Renewable energy generators are given “Green Labels” which can be sold to the distribution companies, on both spot and futures markets. Energy distributors buy these Green Labels in order to prove that they have met their obligation to supply renewable energy.

Enköping, Sweden

Enköping is a town of 20 000 inhabitants where biomass (willow chips, forest residues and sawdust) is used to produce heat and electricity. The boiler is also able to burn oil or propane when starting up.

Steam from the boiler is fed to turbine-generator set with one high pressure turbine and one low pressure turbine section. The exhaust steam from the low pressure turbine passes to two district heating heat exchangers. The power station produces 55 MW of thermal energy for the district heating system and 22 MW of electricity.

Large areas of willow are being grown in the locality. Sludge and waste water from the town, after some treatment, are spread on an 80 ha willow plantation. This is irrigated with 3 mm per day over the 90 day growing season, and the total amount of water applied is 200 000 m³ per year. The plantation annually absorbs 30 tonnes of nitrogen and 1 tonne of phosphorus, which would otherwise have entered the nearby lake Mälaren.
ARBRE Energy Ltd, Yorkshire, England

ARBRE Energy Ltd is nearing completion of the UK’s first large wood-fired power station. This will generate 8 MW of electricity, to be distributed through the local grid.

Each year, about 43 000 dry tonnes of wood fuel will be required. This will be supplied from two sources:
- willow short rotation coppice;
- forestry residues.

Around 1100 ha of willow coppice had been established within a 60 km radius of the plant by the end of 2000, and another 400 ha are expected to be planted in 2001.

The wood, in the form of chips, will be converted to a combustible gas, in a circulating fluidised bed gasifier. The gas will be used to generate electricity in a combined cycle system, incorporating both a gas turbine and a steam turbine.

Biomass fuel (wood chips) will be delivered in road vehicles to the power plant, where it will be weighed and sampled. Loads will be screened to remove oversized particles and metal objects, and held in a reception facility that can store three days supply of fuel. The reception building is fitted with a travelling screw reclaiming in the base, and fuel will be conveyed automatically to a rotary drum drier and dried to 10% moisture content using waste heat. After drying, the fuel will be gasified, and the gas will be cooled and cleaned to remove tars, ammonia and particulates before being compressed and delivered to the gas turbine.

Growing of willow coppice is supported by an establishment grant administered by the Ministry of Agriculture Fisheries and Food (MAFF). Electrical energy sales are supported through the UK government’s Non Fossil Fuel Obligation arrangements, which provide an enhanced price and 15 year supply contract. Farmers provide the fields and carry out initial land preparation using standard agricultural equipment. ARBRE carries out the establishment, management and harvesting, and gives guidance to the farmers throughout the life of the crop.

A second phase, which will involve a 33 MW power plant, is being planned.
Border Biofuels Ltd, Carlisle, England

A new biomass power station is being established by Border Biofuels Ltd at Carlisle, using vacuum pyrolysis to convert wood to energy. The plant will generate 20 MW of electricity, sold through the grid, and is designed so that surplus heat can be used by local businesses on adjacent premises. Electricity sales are being supported through the UK government's Non Fossil Fuel Obligation scheme.

The pyrolysis system produces gas, charcoal and oil. The gas and charcoal will be burned to raise steam for a turbine and generator, and the oil will be used as fuel for a gas turbine and generator. The oil can be stored, allowing the power station output to be matched to demand. Oil is a transportable fuel, and power stations in other locations can generate electricity from wood, using the Carlisle pyrolysis facility.

The wood fuel will be obtained from willow coppice and forestry residues, the site being readily accessible from the large forestry areas of north west England. The power station will be equipped to dry and chip the material as required, to ensure a consistent supply of material suitable for the pyrolysis equipment. Less than one per cent of the wood dry matter will be left as ash, and this will be used as a soil conditioner.

The project will create 27 full time jobs on site, 48 transport jobs and 34 new jobs on the forests.

Weobley School, Herefordshire, England

The wood fuel heating system at Weobley School, installed in 1997, incorporates a 350 kW wood combustion boiler to meet the base load heating requirements of the primary school and the adjacent secondary school.

The fuel, 150 - 300 tonnes of dry chips per year, is supplied from local wood thinnings and from willow and poplar short rotation forestry. Wood chips are delivered twice a week and stored in a concrete silo. Push bars in the silo move the chips to a screw conveyor that feeds the stoking mechanism. Hot water from the boiler is delivered to the school's under-floor heating system. Exhaust gases are cleaned before being released to atmosphere through a chimney stack. Ash produced during combustion and from the exhaust cleaning process is collected and used as fertiliser on the school garden.
3 Growing the crop

Willows thrive in a wide range of soil types, if adequate water is available. The crop is grown from cuttings, mechanically planted. Effective weed control is absolutely essential when establishing a new plantation. Young willows need protection from rabbits and deer. Inputs of fertiliser and chemicals are lower than for most agricultural crops. Disease is controlled by planting a mix of varieties. Willows are sometimes cut back at the end of the first year, to encourage growth of multiple shoots. Plantations can be removed, and the land returned to agricultural crops.

Site selection

**Moisture.** Willows grow best where there is at least 600 mm of rainfall, distributed evenly through the growing season, and moisture available within about one metre of the surface. Willow can grow on land that is too wet for other crops, but areas liable to winter flooding are unsuitable for mechanical harvesting.

**Soil type.** Most agricultural soils with pH in the range 5.5 - 7.5 can be used for willow production. Conventional planting methods require 200 - 300 mm depth of cultivated soil. Dry limestone and chalk areas are not suitable. Heavy clays tend to be cold in spring and this results in slow establishment. Weed control can be a problem on organic soils, because very few suitable herbicides are available.

**Temperature.** Willow can tolerate very low temperatures in winter, but frost in late spring, summer or early autumn will damage the top shoots. Valley bottoms are often frost pockets. Spring and autumn frosts limit the extent of willow plantations to the north more than does the length of the growing season.

**Snow and ice.** In Swedish conditions, heavy wet snow can press down willow shoots and cause them to break at the stump. One-year-old plantations can suffer if they become flooded and ice forms on the surface – the water may drain out, allowing the weight of ice to press the shoots down. Older willows are less vulnerable, because the stems are thick enough to bear the weight of ice.

**Steep slopes** can lead to problems with soil erosion. Harvesting machinery may have difficulty working on slopes greater than about 15%.

**Overhead power cables** must be considered, because willow could reach a height of 7 m before it is harvested.

**Drainage pipes** are liable to become blocked by willow roots. It is best to avoid land that has been recently drained, and to budget for the cost of re-draining at the end of the 15 - 25 year crop cycle.

**Archaeological remains** could be affected where willow plantations are established on land formerly used for grazing or crop production.

**Existing willow trees** are a potential source of plant diseases and willow beetles, and it is best to avoid planting close to them. European Larch trees are an alternative host for the rust diseases that attack willow.

**Road access** is needed in order to transport large quantities of material at harvest.

Willow could touch overhead cables
Fencing

Rabbits will quickly destroy young willows if they gain access to the plantation. Rabbit-proof fencing can form a large proportion of the costs of establishing the crop, particularly for small plantations. Wire netting is generally used, with the lower portion buried or turned horizontally to deter rabbits from burrowing underneath. Electric fences are cheaper, and can be successful if correctly installed and maintained. Machinery is now available to plough in wire netting, and this substantially reduces the cost of rabbit fencing. In Sweden, fencing is not considered economic, and only land with low rabbit populations is used for willow.

Chemical repellents and deterrents have been successful in some instances, but their effects are short lived.

Hares will eat young willow, but are not usually present in sufficient numbers to cause major damage.

Deer fencing is unlikely to be economically justified.

Plantation layout

Row width must be compatible with the harvesting system. A spacing of 0.75 m between rows and 1.5 m alternately between pairs of rows suits most of the currently available machines. With this layout, a spacing of 0.6 m between cuttings along the row gives an overall density of almost 15,000 cuttings per hectare. Recent research tends to favour higher planting densities.

Block length and width affect harvesting operations. Gaps are generally left at intervals through the plantation, to allow access for trailers. A twin-row harvester could fill a 15 m³ trailer with chips over a distance of about 300 m. If material is carried in a bunker on the harvester while road vehicles remain at the headland, the block length must match the bunker capacity.

Headlands must be wide enough (usually at least 6 m) for turning the harvesters and transport vehicles.

Headlands with bare soil can become impassable to traffic during the winter harvesting season, except when the ground is frozen. Grassed headlands reduce this problem. Planting headlands with willow provides a root mat that will help support vehicles; it is important to leave sufficient space between the main rows and the headland rows for any type of harvester that might be used.

Visual impact can be minimised by designing the plantation to fit into the existing landscape, taking account of trees and other features. Hedges around the outside can make a plantation less noticeable in some landscapes. Most harvesters need parallel rows, but they do not have to follow straight lines.
Land preparation

Large stones have to be removed, because they lead to problems during planting, and could cause damage to harvesters. Compacted ground may benefit from subsoiling, to allow easier root development. Land is prepared as for a cereal seedbed, but cultivated more deeply. This usually involves ploughing to a depth of 200 - 250 mm in autumn, before the winter frosts, followed by power harrowing shortly before planting. A good test is to ensure that a person can push a 200 mm long cutting into the ground by hand: if not, machine planting is unlikely to be successful. It is important that the soil should not be allowed to dry out before planting.

Weed control

Weed control is extremely important. Newly-planted willow cannot compete strongly against most weeds, and timing of weed control is critical. Most plantation failures are due to poor weeding.

Prior to planting, weeds are encouraged to germinate and then killed by cultivation or herbicide. Common practice is to apply a translocated herbicide in autumn, with a follow-up application shortly before planting in spring.

After planting, it is usual to apply residual herbicide before the weeds emerge. Provided the surface remains undisturbed, weeds will be killed as they germinate.

Post-emergence spraying may be needed if weeds are still present. The operation requires great care, and must be done before any green colour is visible on the willow buds. A band sprayer can be used to control weeds between the rows after the willow buds have broken, with rubber flaps to protect the crop.

After harvesting, weeds will initially develop faster than willow shoots, but well-rooted willow can often overtake the weeds and close the canopy after mid summer.

Non-chemical weed control. It is difficult to establish a willow plantation without use of herbicides. Deep ploughing helps to bury weed seeds, but is not practical on all soils. Mulches of plastic, paper waste or woodchips are likely to be too expensive. Tined weeders can be used between the rows after planting (up to eight passes may be needed during the first year), but weeds will continue to grow within the rows.

Planting material

Willow is grown from cuttings, which are usually taken from one year old shoots. Even if older shoots are harvested as planting material, only the one year old part is used – two year old wood has relatively few buds that break immediately after planting, the other buds appear much later and allow weed competition to develop.

In the traditional hand planting technique, still used for small scale (eg nursery) production, cuttings are generally 180 - 200 mm long and at least 8 mm in diameter. Each cutting is pushed vertically into the soil to 90% of its length, to ensure it has access to moisture. Shorter cuttings can be satisfactory during a wet growing season, but suffer if the soil dries out rapidly. Thinner material is not often used because:

- xylem vessels are easily broken when cutting are pressed into the soil;
- there may be insufficient reserves to withstand a drought period.
Cuttings are kept in cold stores, often at -2°C to -4°C, to ensure that all physiological processes are halted, and to prevent moulding. Transferring cold cuttings into direct sunlight could seriously damage the plants: ice crystals that have formed within the plant cells in the cold store must be allowed to melt slowly in shade before cuttings are taken to the field. After thawing, cuttings may be kept for short periods in sealed polythene bags at +2°C to +4°C.

Willow cuttings suffer if allowed to dry out. They can be covered with plastic sheeting to minimise evaporation. Any cuttings that have become partly dried during storage need to be soaked or sprayed with water before planting.

**Planting machinery**

_Transplanters_, similar to those used for vegetable seedlings, can be adapted to plant willow cuttings, but the operation is labour intensive.

_Cut-and-plant machines_ have been used successfully for large areas of willow coppice. Long willow sticks, fed by hand into the mechanism, are pressed vertically into the soil to a depth of 200 mm and automatically cut just above ground level. Four-row machines planting 20 000 cuttings/ha can achieve work rates of 6 - 8 ha/day. Planting material need careful selection: sticks must be reasonably straight in order to feed through the mechanism.

It is usual to roll immediately after planting, pressing soil around the cuttings. The soil should be firm enough to prevent a person pulling cuttings out of the ground using finger and thumb.

_Alternative planting techniques_. One new method uses a high speed _billet planter_ to drop short pieces of willow (50 - 100 mm long) into grooves in a cultivated bed. There is no control over the exact location of each piece: some lie horizontally in the soil, and may not grow well if there is a drought after planting.

Another new technique is _layflat planting_. Full length sticks are planted horizontally in small furrows and covered with 20 - 50 mm soil, the shoots appearing from each growing point along the stem. Layflat planting is fast and cheap, employing simple machinery. Vigorous growth is established very quickly – planting long sticks means there are substantial energy reserves for growth, and no cut surfaces where moisture might be lost or diseases might enter.

Billet and layflat planting need further development work and experience to give reliable systems. However, they offer potential to substantially reduce the cost of establishment.

**Plant breeders’ rights**

The right to multiply varieties generally belongs to the plant breeder. New techniques such as billet and layflat systems allow planting material to be produced at moderate cost, but it is important to note that:

- material produced by the grower may be inferior to that from a specialist nursery;
- development of improved varieties can only continue if the breeders receive the royalty payments due to them.
Energy from Willow

Planting date
Willow is generally planted in spring, though planting from December through to June is possible. Early planting leads to more problems with weed control. Later planted crops need less herbicide, but are more susceptible to drought.

Manuring and liming
Fast-acting fertilisers are not generally used in the crop's first year, as they tend to increase weed growth.

Sewage sludge, in the form of cake or pellets, can be applied before planting. Sludge is analysed to ensure that heavy metals and organic solvents will neither contaminate the land nor be released to atmosphere during combustion of the crop. Sludge applied in Sweden is incorporated into the soil. UK growers have applied liquid bio-solids in the second year by hosereel irrigator and dribble bar.

Lime, where needed, is applied before planting or immediately after harvest. Applications of lime-stabilised sewage sludge can be used to raise the pH.

Winter harvesting ensures that nutrients in the leaves are returned to the soil. Annual fertiliser applications equivalent to 60 - 80 kg/ha nitrogen, 10 kg/ha phosphate and 35 kg/ha potash have been recommended in Sweden, to replace nutrients removed when harvesting the stems. Ash from combustion of willow can be spread in the plantations, to return phosphate, potash and micro-nutrients to the soil.

Pest and disease control
Integrated Pest Management systems are usually recommended. Total elimination of pests and diseases is neither desirable nor economically justified.

Insects. Leatherjackets can damage willow planted after grass or long term set-aside, and an insecticide spray is sometimes needed. Beetles, sawfly larvae and aphids will attack the leaves and stems of willow, but moderate numbers have little effect on yield. Overall spraying would rarely be either practicable or economic. Local application of insecticide using a fan-assisted sprayer may be justified in case of a severe attack by willow beetles, which can reach epidemic proportions. Sacrificial planting to attract beetles away from crop areas is being investigated.

Slugs sometimes cause damage after planting, particularly on heavier soils. The most effective precaution is to roll the land after planting, but slug pellets are occasionally required.

Diseases. Willows are susceptible to rusts that affect the leaves and stems. Although these rusts can be controlled by fungicides, it is not economic or practical to do so. A strategy of planting at least five varieties per site helps to minimise the effects of the disease, and breeders are endeavouring to produce more resistant varieties.

Growers in Sweden have in the past used a mosaic layout, with 1 - 2 ha blocks of each variety. The introduction of cut-and-plant machines, and recent developments in billet planting and layflat planting, have made it easier to establish an intimate mixture of varieties. Intimate mixtures are generally more effective, and allow for yield compensation where a component of the mixture becomes sensitive to rust.
Growing the crop

Irrigation

Normal irrigation is not economic, but willow is sometimes employed as part of a water treatment system. The waste water is made more environmentally acceptable by removal of nitrates, phosphates and some heavy metals, and the water and nutrients can increase willow production.

Cutting back

Newly established willows are often cut back to ground level at the end of the first year, and this encourages the plants to produce multiple stems (true coppicing). The operation must be completed before the buds break. There is usually very rapid growth after cutback.

The decision on whether to cut back depends on the varieties used, the number of shoots per stool and the amount of weed growth. With some older varieties, the first year shoots grew in a very curved shape, close to the ground, but cutting back caused subsequent stems to grow straight. Other varieties may show little benefit from cutting back.

Machines for cutting back are generally based on reciprocating grass mowers or oilseed rape swathers. A clean cut is essential – flail mowers and drum or disc mowers cause too much damage to the stools. Low ground pressure tyres are used to reduce the risk of soil compaction.

Weeds may grow after cutback. It is advisable to use a contact herbicide, allowing a delay of 24 - 48 hours for wound healing, but ensuring that herbicide is applied before the willow starts to re-grow. If this fails it may be necessary to use a selective herbicide or inter-row spraying. Inter-row cultivation is not feasible after cutback because of willow roots near the surface.

Plantation removal

Economic life of a willow plantation is expected to be up to 25 years, though this has not yet been proved under UK conditions. Some farmers may want to re-plant earlier if improved varieties become available, or if the economics of production change.

Swedish experience indicates that land growing willow coppice can be returned to agricultural production without major difficulties. The coppice stools have to be killed using herbicide after the final harvest. Ploughing, followed by use of a heavy disc harrow or rotary cultivator, will then break down the stools. In practice this usually involves at least one “fallow” year before the land returns to agriculture.
4 Supplying fuel to the end user

The willow has to be cut, removed from the field, and delivered to the end user. Organising this supply chain on a large scale is not a simple matter. The crop is generally too small to handle with conventional forest machinery, yet too woody to be harvested by conventional agricultural equipment. Mechanisation systems are still being developed and are likely to change during the life of a plantation.

**Need for storage.** For winter heat production, the willow can be harvested and used immediately, with only small temporary stores needed. Much greater storage capacity is required when producing electricity or process heat throughout the year.

**Time of chipping.** Most end users need chipped material. It is easy to chip willow during harvesting, but freshly-harvested chips tend to decompose in a store unless a drying system is installed. Alternatively, the crop can be harvested as long sticks (which suffer much less deterioration during storage, but are difficult to handle mechanically) and chipped shortly before use.

### Types of harvesting system

<table>
<thead>
<tr>
<th>Harvesting system</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest and chip in one operation</td>
<td>Most developed and cheapest system at present, but long term storage may involve costly drying to prevent mould growth</td>
</tr>
<tr>
<td>Harvest full length sticks, to be chipped later</td>
<td>Equipment needs further development, but storage likely to be easier</td>
</tr>
<tr>
<td>Gather sticks into bundles or bales during harvest</td>
<td></td>
</tr>
</tbody>
</table>

### Harvesting season

Willow harvesting is normally restricted to the winter months (November - February in northern Europe) in the period after leaf fall and before leaf set. An extended harvest period of late September to June is possible, but may lead to:

- higher moisture content at harvest;
- blockage of harvesters by leaf material;
- problems of contamination within the energy conversion equipment;
- reduction in long-term yield, as nutrients in leaves are not returned to the soil;
- reduced biodiversity.

In Sweden the optimum harvest season is December - March, when the ground is frozen (and can therefore support machinery) and the snow depth is low. In UK there are fewer problems from snow, but the land cannot always carry vehicles and machines.
**Harvesting cycle**

Willow for energy production has generally been harvested on a three year cycle. Harvesting on a 2-year, 4-year or 5-year cycle can be considered, depending on the rate of crop growth and the demand for fuel. Stem thickness influences the type and quality of fuel produced: shorter harvesting cycles will produce thinner stems, with a high proportion of bark. Delayed harvesting results in larger diameter stems, which need robust machinery.

**Cut-and-chip harvesting**

In a cut-and-chip system the willow chips are discharged to a trailer pulled alongside or behind the harvester, or carried on the harvester in a bunker.

Large self propelled machines, one a forage harvester and the other a sugar cane harvester, have been widely used in field trials. Smaller, trailed and tractor-mounted harvesters have been developed. Overall work rates have been in the region of 0.6 ha/h with large self propelled machines, and 0.2 - 0.3 ha/h with tractor-mounted harvesters.

In northern Europe, forage harvesters can be used on other crops (grass, maize, etc) outside the willow harvesting season.

Harvester designers have experienced some problems in cutting willow sticks from the coppice stools and achieving a reliable flow of material through the machines. Many of the delays reported in trials were caused by blockages. Forage harvesters and sugar cane harvesters can generally chop willow into small pieces with little difficulty, but the particle size and shape are not always ideally suited to the energy conversion equipment.

**Billet (chunk) harvesting**

Field operations are similar to cut-and-chip harvesting, but the willow is left in pieces 100 - 250 mm long, rather than as small chips. Billets are less dense than chips, and this affects transport costs.

**Harvesting loose sticks**

Equipment for harvesting willow as full length sticks ranges from trailed implements to a large self-propelled machine based on a combine harvester chassis.

A practical stick harvester must collect the crop in a bunker and deposit heaps, preferably onto a hard surface at the headlands. If heaps have to be picked up from within the coppice area, it may be very difficult to achieve work rates that compare with cut-and-chip harvesting systems.

Any harvester that carries full length willow sticks in a horizontal position will be long, and require wide headlands for turning.
**Bundling and baling**

Machines that produce bundles or bales of willow sticks have not yet been developed sufficiently for large scale harvesting.

**Bundles of full length sticks** do not suit standard road vehicles because the bundle length depends entirely on the crop height. The bundles tend to be of variable shape, and difficult to stack.

Prototype **continuous bundling machines** have been designed to bind willow into a continuous "sausage" from which lengths are cut off and dropped in the field.

**Roll balers** tested so far have not been able to produce dense bales from three year old willow, or to achieve the work rates needed for commercial harvesting.

**Rectangular bales** would make efficient use of vehicle capacity and storage space, and small numbers have been produced during a research project. Agricultural ram-type balers may not be strong enough to handle willow reliably, because the feed mechanism must be capable of bending the thickest stems that might be harvested. It should prove easier to make bales from willow billets, rather than full length sticks, because billets of an appropriate length would not need to be bent in the feed mechanism.

A practical baling or bundling system must allow collection from the field at low cost. Picking up single bales/bundles by loader or forwarder is likely to be slow and expensive. Self-loading trailers might perhaps be developed along the lines of those used for straw bales, but an accumulator that deposited bales/bundles at the headland would probably be a better approach. Another option being investigated is use of a stick harvester in the field, with bundles or bales produced at the headland.

**Stem cutting mechanisms**

The harvester must be able to:
- sever the stems at 50 - 100 mm above ground level;
- cut stems of any diameter likely to be encountered (possibly more than three years old, in case harvesting is delayed);
- deal with tangled stems;
- leave a smooth cut surface.

Most harvesters use circular saw blades to cut the crop. Flail cutters and blunt toothed discs tend to damage the coppice stools and split stems below the level of the cut, increasing susceptibility to disease. Excessive cutting height can leave the stools in a ragged state, as the stems deflect easily away from the cutting mechanism.

Circular saw blades can carry snow into the harvester and so raise the moisture content of the crop. This is not generally a problem in UK or the Netherlands, but is an important consideration in Sweden. One type of harvester cuts the crop with a chain saw blade, and this does not introduce snow into the mechanism.
**Trafficability and soil damage**

Compaction and rutting affect willow roots, and may reduce yield, especially during the first rotation.

Harvesting in Sweden is often carried out at very low temperatures, with machines supported on frozen ground. In UK the ground can be wet for much of the harvest season, therefore machines and wheel equipment must be carefully specified – a large self-propelled coppice harvester may weigh as much as 14 tonnes.

Willow roots form a supporting mat within the coppice area, but vehicles are liable to sink on un-cropped headlands. Sacrificial planting of headlands may be considered for some soils and climates. Harvesters on large tyres or tracks usually travel over wet ground without difficulty, but there can be problems if standard agricultural tractors and trailers are used for transport.

Tracked machines cause less damage than wheels. Agricultural trailers can be fitted with tracks for transport on fields and farm roads.

**Harvesting losses**

In any harvesting system there may be losses due to incorrect cutting height, particularly on uneven or rutted land. Where chips are blown from the harvester to a trailer, there are likely to be additional losses due to operator errors (misalignment of discharge spout, spillage from over-filled trailers, missed gear changes, etc).

**Handling and transport**

In a small willow energy scheme, agricultural trailers can carry material directly from the field to the power plant. Large scale operations usually involve extra handling, with the crop stored on the farm and then transferred to road vehicles.

Handling and transport costs are likely to be substantial, but are not particularly sensitive to changes in haulage distance because:

- average speeds tend to increase as distances increase;
- turn-round times (loading, unloading, weighing, sampling, etc) remain the same irrespective of distance.

Loads of dry willow are much less than the rated payloads for standard vehicles (bulk tippers for chips, flat-beds for bales, log-carriers for full-length sticks). Hauling moist willow increases the load weight, but not the amount of dry matter carried. Freshly-harvested chips could exceed the load capacity of a road vehicle.

A compactor system available for silage trailers might be suitable for willow chips. The trailer front panel is pushed rearwards, compressing the load, and then drawn forward so that more material can be added at the front. The push-off mechanism empties the trailer without tipping, and might also be applied to demountable containers or to lorry/trailer combinations. Forcing material to the rear of the trailer will inevitably reduce weight transfer to the tractor wheels – this could cause traction problems on wet fields or icy roads.
Secure loads are essential for road haulage, though unsecured loads may be acceptable for short haul transport from field to farm steading. Bulk loads of chips can be covered using automatic sheeting systems, which are already to fitted to many lorries. Bales of willow produced in experiments have been less uniform than straw bales, loads might be considerably less stable, and strapping arrangements would probably have to be improved over those currently adopted for straw bale transport.

<table>
<thead>
<tr>
<th>Probable loads for large lorries</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOTE: Information on densities, particularly for bales, has been derived from a very small number of experiments, and may be subject to a lot of variation.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Load carried</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>@ 50% mc</td>
</tr>
<tr>
<td>80 m³ chips (25 - 50mm)</td>
<td>22.4 t</td>
</tr>
<tr>
<td>140 kg dry matter per m³</td>
<td></td>
</tr>
<tr>
<td>80 m³ billets (200mm)</td>
<td>14.4 t</td>
</tr>
<tr>
<td>90 kg dry matter per m³</td>
<td></td>
</tr>
<tr>
<td>30 rectangular bales (1.2 m x 1.2 m x 2.4 m)</td>
<td>21.8 t</td>
</tr>
<tr>
<td>105 kg dry matter per m³</td>
<td></td>
</tr>
<tr>
<td>40 rectangular bales (1.2 m x 0.7 m x 2.4 m)</td>
<td>16.9 t</td>
</tr>
<tr>
<td>105 kg dry matter per m³</td>
<td></td>
</tr>
<tr>
<td>60 roll bales (1.2 m diam x 1.2 m wide)</td>
<td>17.1 t</td>
</tr>
<tr>
<td>105 kg dry matter per m³</td>
<td></td>
</tr>
</tbody>
</table>

Some countries impose restrictions on load height for road vehicles, and this will be important if a baling system is adopted. A typical flat-bed lorry has a platform height of about 1.2 m, so that loading the largest rectangular bales (1.2 m x 1.2 m x 2.4 m) three high results in an overall height of 4.8 m. Smaller bales become appropriate if there is a height restriction.
Supplying fuel to the end user

Drying and storage

Freshly harvested willow contains over 50% moisture. Dry material is preferred for combustion, and essential for gasification or pyrolysis.

**Willow sticks** dry naturally during storage. Under typical European conditions the moisture content will eventually fall to 15 - 25% unless the material is re-wetted by rain. Heaps of sticks are sufficiently permeable to allow cooling by natural convection. Bundles or bales of willow sticks could probably be stored without major deterioration.

**Stacks of wet chips** quickly heat up and start to decompose. Temperatures of 60°C can be reached within hours. Much of the energy value may be lost, and mould spores are a health hazard. This is a major issue for cut-and-chip harvesting systems.

Storage characteristics of **billets** are intermediate between those of sticks and chips.

**Chips can be dried** successfully, and then stored with little further loss of dry matter. Grain drying techniques have been adapted for willow chips, though the material is less dense than grain and does not flow so readily.

**Ventilated floor driers** operating at near-ambient temperatures can dry willow chips from 50% to 15% in about three weeks. Batch driers of the drive-on floor type, using higher air flows and temperatures up to 40°C, should be able to dry willow in 1 - 2 days.

High temperature rotary driers are an option for large scale operations, but not generally economic for individual farms. Most continuous grain driers can only work with flowable materials, though the conveyor type may be adaptable for willow chips. Volatile components can create atmospheric pollution in the form of "blue haze" where wood fuel is dried at temperatures above 100°C.

**Low rate aeration** can be used to minimise moulding and dry matter loss from a stack of wet chips, built over a simple perforated duct fitted with a small fan.

**Airtight storage** can greatly reduce dry matter losses, but commercial scale methods have not yet been developed.

**Density of willow fuel is low**, therefore large volumes have to be stored. Many farms have suitable areas available, but storing large quantities at a power station may be impractical.

**Chipping after harvest**

Freshly harvested willow can be chipped using less energy than sticks that have dried during storage.

If sticks are chipped in a separate operation, a large static machine at the power plant will probably be more economical than either small individual chippers on farms or a larger mobile chipper moved from site to site.

Where crops are delivered from a number of different cut-and-chip harvesters, it may be necessary to screen and re-chip at the power station in order to meet the specifications of a gasifier or pyrolysis plant. Many of the energy schemes being developed will use forest residues in addition to willow coppice, and will require a chipper on site.
5 Converting willow to energy

Willow can be burned directly to produce steam for a turbine, or hot water for space heating. Alternatively, the crop can be converted to gas or oil and used in a gas turbine or internal combustion engine to generate electricity.

Willow is converted to energy using thermochemical processes (i.e., they involve both heat and chemical reactions) of combustion, gasification, or pyrolysis.

Combustion technology is already well established. Gasification and pyrolysis are not new, but their use in generating energy from willow is still in the development stage.

Combustion

Combustion is generally the most economical way to produce heat from biomass. It involves burning the crop with enough oxygen to convert nearly all the material to carbon dioxide and water. The heat emitted can be used directly (e.g., to produce hot water in a central heating system) or it can raise steam and drive a steam engine or turbine to generate electricity.

Equipment ranges from very small wood stoves used for domestic heating (e.g., 15 kW thermal capacity, wood consumption 3.5 kg/h) to very large systems producing several hundred MW of heat. The upper limit is restricted by local energy demand and availability of biomass rather than by combustion technology. Equipment design depends on the moisture content and particle size of the fuel.

Wood stoves fed with chips by a screw stoking mechanism are commercially available up to several MW capacity. Flue gas emissions can be a problem with the simpler designs of small wood stoves. Air is supplied at different locations (primary, secondary, and sometimes tertiary air supply) to ensure complete combustion at high efficiency and to reduce flue gas emissions.

In a grate burner, fuel is fed from the top and moves downwards by gravity, the ash being discharged at the bottom. Disadvantages of fixed grates are the danger of fuel avalanches, uneven distribution of fuel over the grate, and difficulty in controlling the process conditions. More even distribution of fuel can be achieved by a moving grate (incorporating a conveyor or slowly moving platform) or vibrating grate.

A pile burner consists of a refractory lined combustion chamber with a grate at the base. Pile burners are simple in design and suitable for a broad range of fuels, but it is difficult to control the process conditions, and local high temperatures can occur leading to high emissions of oxides of nitrogen (NOₓ). Most pile burners consist of several identical cells. In order to discharge the ash, a cell must be shut down and cleaned manually after cooling.
**Entrained combustion** is a system where air flow carries small fuel particles (maximum 5 mm x 5 mm x 5 mm) into the combustion chamber. The total quantity of air used is much greater than would be required to oxidise the fuel. As a result, a lot of flue gas is produced, and the heat lost in the flue gas leads to a relatively low efficiency.

**Fluidised bed combustion** is widely used in modern large installations. Fuel particles, together with an inert bed material such as sand, can be “fluidised” by air movement. In *bubbling* fluidised beds, the material behaves like a boiling fluid, but is not transported by the air stream. In a *circulating* fluidised bed, the gas velocity is higher so that part of the bed material leaves the reactor vessel; the solids are transported back to the reactor vessel *via* a cyclone and return pipe. Combustion temperature in a fluidised bed is relatively low and easily controlled, so that NOX emissions can be kept low. Additives such as limestone can be used to combine with sulphur and/or chlorine and thereby reduce emissions of sulphur dioxide and hydrogen chloride.

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### Emissions resulting from combustion

The flue gases from biomass combustion contain some contaminants. Nitrogen in the biomass can lead to the production of NOX in the flue gas. In addition to “fuel NOX,” some “thermal NOX,” is produced when nitrogen and oxygen combine at high combustion temperatures (especially > 1400 °C). Incomplete combustion can lead to enhanced concentrations of carbon monoxide and hydrocarbons. Flue gases often contain some dust. Willow generally has low sulphur and chlorine content, therefore sulphur dioxide and hydrogen chloride are only present in small quantities in the flue gases. Emissions of heavy metals and dioxins are relevant for waste combustion rather than willow. Flue gas emissions can be reduced by:

- primary measures (choice of fuels leading to low emissions);
- secondary measures, during combustion (eg staged supply of combustion air);
- tertiary measures (“end of pipe” techniques such as filtration of flue gases).

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**Gasification**

Gasification (heating with restricted air supply) converts solid organic material into a combustible gas that is generally used in an engine or gas turbine.

It is not economic to transport or store the gas, because it has a low calorific value in relation to its volume. The gas is normally used immediately, to generate electricity.

**Internal combustion engines** can run on gas produced from willow, with only minor modifications needed. Gas cleaning is required to remove particles that might erode the pistons and cylinders, acids or alkalis that could cause corrosion, and tar or gum that might cause valves or piston rings to stick.

Spark ignition engines need uniform quality of gas. A compression ignition (diesel) engine can tolerate more variation in gas quality, but requires a small proportion of the fuel to be supplied as diesel. In general a minimum of 7% diesel is needed; this can be increased up to 100% in periods when gas is unavailable.

An engine fuelled from a gasifier can operate at about 80% of the power it would produce using diesel. The calorific value of the gas is only 4 - 5 MJ/m³ (compared with about 40 MJ/m³ for methane), but the air-fuel ratio is easily adjusted to compensate for this.
**Energy from Willow**

Gas turbines can be fuelled by gas produced from willow, provided it has been adequately cleaned. They are generally used for large power stations, but efficient gas turbines of only a few hundred kW are now available. A gas turbine is much smaller and lighter than a reciprocating engine of similar output.

Modern power stations often employ **combined cycle generation**. Fuel is burned to power a gas turbine, and the hot exhaust is then used in a boiler to produce steam, which powers a steam turbine. Using the exhaust in this way results in a major improvement in overall efficiency.

Gasification is sometimes used in heat production because:
- a gas burner is simple;
- it is easier to control a gas burner than a biomass furnace;
- very little excess air is used, so there is minimal loss of heat through the flue gases;
- burning the gas produces no particulates.

The type of gasifier used depends on the size of the installation, the quality of fuel available, and the quality of gas required.

With a **downdraft gasifier**, biomass fuel is fed in at the top, gas is sucked off near the base, and air is drawn down through the fuel.
- Size, shape and moisture content of the biomass particles must be controlled within close limits.
- Quality of the gas fuel produced is generally good.
- The downdraft principle is only suitable for installations of less than about 1 MW electrical output.

An **updraft gasifier** is one where the gas flows upwards as the biomass moves down.
- The updraft principle is suitable for installations of a few tens of megawatts capacity.
- Size, shape and moisture content of the biomass particles are much less critical than with a downdraft gasifier.
- Quality of the gas produced tends to be poor.

Other types of fixed bed gasifier, produced in small numbers, may involve:
- cross flow design;
- use of oxygen as the gasifying agent instead of air;
- feeding from the bottom by means of a transport screw.

**Fluidised bed gasifiers** have either a bubbling bed or a circulating bed.
- There is no technical scale-up limit (though size may be limited by availability of biomass or the local energy demand).
- The gasifying agent is usually air at atmospheric pressure, but pressurised gasification can be advantageous when supplying gas turbines larger than about 100 MW.
- The danger of ash agglomeration is low, because of the relatively low temperature (about 850 °C).

In **entrained flow gasifiers** the gasifying agent is supplied at high velocity so that pulverised biomass is pneumatically transported through the reactor. Oxygen is used instead of air as the gasifying agent, in order to achieve high conversion efficiency despite a low residence time in the reactor. Entrained flow gasification is only economically feasible above 200 MW thermal capacity.
Pyrolysis

Pyrolysis involves heating in the absence of oxygen (rather like traditional charcoal production) to produce a liquid fuel and a solid char, together with combustible gas. The composition of pyrolysis products depends on the heating rate, residence time and temperature, as well as on the composition of the fuel.

<table>
<thead>
<tr>
<th>Heating rate [K/s] *</th>
<th>Residence time</th>
<th>Max temp °C</th>
<th>Main product</th>
</tr>
</thead>
<tbody>
<tr>
<td>slow pyrolysis</td>
<td>&lt;&lt; 1</td>
<td>hours / days</td>
<td>400 600</td>
</tr>
<tr>
<td>fast pyrolysis</td>
<td>500 - 100 000</td>
<td>0.5 - 5 s</td>
<td>650</td>
</tr>
<tr>
<td>flash pyrolysis</td>
<td>&gt;10⁶</td>
<td>&lt; 1 s</td>
<td>&lt; 650</td>
</tr>
<tr>
<td></td>
<td>&lt; 1 s</td>
<td>&gt; 650</td>
<td>gas</td>
</tr>
</tbody>
</table>

* degrees per second

Pyrolysis oils:
- have a calorific value of 16 - 18 MJ/kg (about half that of diesel fuel);
- can be used as fuel for stationary engines or turbines generating electricity, but are not suitable for road vehicles;
- can be stored in tanks or transported for use in other locations;
- tend to contain a lot of water, and to be acidic (corrosive to mild steel tanks and pipes);
- are sometimes viscous and difficult to pump;
- may decompose at high temperature and deteriorate if exposed to air.

Oil production from wood is still under development. Intensive research is being done world-wide, either on reactor development for improved process economy, oil yield and quality and on oil upgrading.

Other energy conversion technologies may be adopted in future.

The Stirling engine is a type of reciprocating engine that has been proposed for renewable energy installations. Like the steam engine, it uses external combustion (the "working fluid" inside the cylinder, which is often air, does not come into contact with the fuel), and can operate using any type of heat source. High efficiencies are possible, but the Stirling engine, although first patented in 1827, has never been widely adopted.

A fuel cell is a device that produces electricity from a fuel, usually hydrogen. In principle, it should be possible to gasify willow and then pass the gas through a fuel cell to generate electricity, but this is not likely to be commercially applicable in the near future.
6 Fuel characteristics

Moisture content, particle size, particle shape and chemical composition all affect the performance of energy conversion equipment. The designer of a willow energy system, and anybody involved in the supply chain, needs information on these fundamental characteristics of the fuel.

Wood fuel that is acceptable to one user might be quite inappropriate for a different energy conversion process. Fuel quality may be very variable, and many installations will need to use fuel from more than one source (e.g., both forestry residues and willow).

Moisture content will have to be measured whenever energy crops are traded. For some energy conversion systems the moisture content must be within close limits. If loads are liable to be rejected for excessive moisture content, testing must be rapid. Where testing is used simply for calculating payments (e.g. if all the crops pass through a drier at the power station) the speed of assessment is less important.

Particle size and shape affect the way fuel flows and the surface area available for chemical reactions. Gasification and pyrolysis usually require small particles (willow chips). Chips are also needed for most large scale combustion systems, to allow automatic stoking, though some types of furnace may be able to burn whole bales or bundles of willow. Uniform chip size is important for certain energy conversion systems, but some harvesters tend to split willow stems and produce a lot of very small particles. Oversized material is liable to cause blockages or "bridging" in feed systems.

Chemical composition affects the quantities of:
- energy obtainable from the fuel;
- ash and solid deposits produced;
- contaminants to be cleaned from the flue gases.

Ash content may be high if soil enters the harvester, or is picked up when handling crops that have been stored on the ground.

Fuel supply standards. Information on biomass fuels has been collated at ECN into the "Phyllis" database. An example of the composition of willow is reproduced below.

<table>
<thead>
<tr>
<th>Proximate analysis [% by weight, as received]</th>
<th>Ultimate analysis [% by weight, on dry basis]</th>
</tr>
</thead>
<tbody>
<tr>
<td>moisture</td>
<td>C</td>
</tr>
<tr>
<td>volatiles</td>
<td>H</td>
</tr>
<tr>
<td>fixed carbon</td>
<td>N</td>
</tr>
<tr>
<td>ash</td>
<td>O</td>
</tr>
<tr>
<td>Heating value [kJ/kg as received]</td>
<td>S</td>
</tr>
<tr>
<td>LHV a.r. (as received)</td>
<td>Cl</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elementary analysis [mg/kg on dry basis]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
</tr>
<tr>
<td>As</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>Ca</td>
</tr>
<tr>
<td>Co</td>
</tr>
<tr>
<td>Cr</td>
</tr>
<tr>
<td>Cu</td>
</tr>
<tr>
<td>Fe</td>
</tr>
<tr>
<td>K</td>
</tr>
<tr>
<td>Mg</td>
</tr>
<tr>
<td>Mn</td>
</tr>
<tr>
<td>Na</td>
</tr>
<tr>
<td>Ni</td>
</tr>
<tr>
<td>P</td>
</tr>
<tr>
<td>S</td>
</tr>
<tr>
<td>Si</td>
</tr>
<tr>
<td>Ti</td>
</tr>
<tr>
<td>V</td>
</tr>
<tr>
<td>Zn</td>
</tr>
</tbody>
</table>

Photo: SAC

Forestry residue | Willow
Chip size and shape depend on the material and the harvesting machinery
## Fuel characteristics

**Sampling.** There may be a lot of variation within a load, therefore samples will have to be large. New techniques may have to be developed to take representative samples from bales or bundles.

### List of properties and characteristics of biomass

Designers of energy conversion equipment may need information about a wide range of fuel characteristics, as indicated in the table below.

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Unit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>moisture content</td>
<td>mc</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>dimension(s)</td>
<td>mm</td>
<td></td>
<td>sawdust, shavings, chips, lumps, logs, trunks</td>
</tr>
<tr>
<td>shape</td>
<td></td>
<td></td>
<td>cubes, pellets, sticks, fibres</td>
</tr>
<tr>
<td>calorific value</td>
<td>LHV</td>
<td>kJ/kg</td>
<td></td>
</tr>
<tr>
<td>type (species)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ash content</td>
<td>a</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>ash composition</td>
<td></td>
<td>%</td>
<td>oxides i.e. Fe₂O₃, CaO, SiO₂, Al₂O₃ etc.</td>
</tr>
<tr>
<td>raw bulk density</td>
<td></td>
<td>kg/m³</td>
<td></td>
</tr>
<tr>
<td>true specific gravity</td>
<td></td>
<td>kg/m³</td>
<td></td>
</tr>
<tr>
<td>angle of repose</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Flowability”</td>
<td></td>
<td></td>
<td>important for handling and storage (bridging)</td>
</tr>
<tr>
<td>volatile matter</td>
<td>vm</td>
<td>%</td>
<td>in particular light weight components that tend to escape while drying reported separately</td>
</tr>
<tr>
<td>strength, durability</td>
<td></td>
<td></td>
<td>for coal standards for the “grindability” have been developed (i.e. Hardgrove) also “size stability”, “friability” and “test for dustiness” may be useful</td>
</tr>
<tr>
<td>fermentation</td>
<td></td>
<td></td>
<td>degradation of large stacks of (moist) wood reduce heating values and increase danger of fire</td>
</tr>
<tr>
<td>dust explosions</td>
<td></td>
<td></td>
<td>ignition energy for dust generated from wood in handling and drying equipment</td>
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<td>sulphur</td>
<td>S</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>nitrogen</td>
<td>N</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>chlorine</td>
<td>Cl</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>fluorine</td>
<td>F</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>composition:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- carbon</td>
<td>C</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>- hydrogen</td>
<td>H</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>- oxygen</td>
<td>O</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>major dilutions</td>
<td></td>
<td>mg/kg</td>
<td>Al, Si, K, Na, Ca, Mg, Fe, P, Ti...</td>
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<tr>
<td>minor dilutions</td>
<td></td>
<td>mg/kg</td>
<td>As, Ba, Cd, Be...</td>
</tr>
<tr>
<td>heavy metals</td>
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<td>mg/kg</td>
<td>Sb, Pb, Cr, Cu, Mn, V, Sn, As, Ni, Se, Te the sum of these is specifically limited in Dutch emission regulations</td>
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<tr>
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<td>mg/kg</td>
<td>Cd and Hg reported separately</td>
</tr>
<tr>
<td>energy density</td>
<td></td>
<td>kJ/m³</td>
<td></td>
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<td>ash fusion behaviour</td>
<td>t</td>
<td>°C</td>
<td>initial deformation, softening, hemispherical and fluid temperature for oxidising and reducing conditions</td>
</tr>
<tr>
<td>ash fouling potential</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>fixed carbon</td>
<td>cf</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>C/N ratio</td>
<td>c/n</td>
<td>-</td>
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7 Environmental considerations

Producing energy from willow does not contribute to global warming.
Willows provide an attractive habitat for a wide range of plants, animals, insects and birds.
Vehicle movements tend to occur through the winter months.
Cultivation of willow can help to clean up contaminated land or contaminated water.

Greenhouse gases, global warming. Producing energy from willow does not increase the amount of carbon dioxide or other greenhouse gas in the atmosphere: burning plant material releases only the same amount of carbon dioxide as was taken up when the tissues were being formed by photosynthesis.

Willow contains very little sulphur, therefore combustion does not create major problems of sulphur dioxide emissions or acid rain.

Energy balance. The energy obtainable from willow can be around 20 times as much as was used to grow the crop.

Flora and fauna. Growing willow coppice is a very effective means of increasing biodiversity, particularly where it replaces intensive agricultural crop production or spruce plantations.

Many shade-tolerant plants thrive within willow plantations. Blocks are harvested at 2 - 5 year intervals, sites are unlikely to be completely cleared, there are always some areas in each age class, and the result is a variety of habitats. Willows provide ecological corridors for movement of all types of fauna.

Insecticide use is minimal in energy coppice, large numbers of insects are usually present and provide a food source for birds and small mammals. Bats, shrews, hedgehogs and voles thrive, while butterflies and beneficial insects are often present in large numbers.

Willows provide excellent game cover. Pheasants, snipe and deer and rabbits favour the shelter provided by the older plants. Winter harvesting means that there is no disturbance to birds during the breeding season, or to summer migrants. Newly harvested areas attract lapwings, skylarks and partridges.

Transport operations. Small willow-to-energy schemes are likely to involve small numbers of vehicle movements, often by agricultural trailers, and have only minor effects on local traffic.

Larger schemes will mean that willow has to be hauled by large lorries. When developments are being planned, it is important to consider the likely effects of such traffic on the local environment (noise, emissions from vehicle exhausts, etc) and on maintenance requirements for rural roads and bridges. Traffic flows associated with willow are likely to be highest in winter: where willow replaces cereals or grass silage, there could be an overall reduction in summer traffic on rural roads.
Visual impact. Willow plantations help create diversity in the landscape. With a mixture of varieties (to reduce disease problems) there is a mix of vegetation colours. Some areas are cut each year, and the result is an ever-changing landscape with a gradation of crop heights. Willows are taller than most agricultural crops, and liable to obscure the view from roads or footpaths.

Pollution from willow energy conversion. At a power station converting willow to energy, it is impossible to entirely avoid pollution from noise, dust and odours. A steam plume may be visible under certain weather conditions. Emissions may include “blue haze” if the willow is dried at high temperatures. However, a modern biomass power station should cause less atmospheric pollution than an existing fossil fuel system.

Ash disposal. Converting willow to energy produces some ash, which can often be used as a fertiliser. Other methods of disposal may have to be considered if the quality of the ash is low (eg containing heavy metals due to growth of the willow on contaminated soil). Ash can be incorporated in some types of concrete.

Using willow to reduce pollution. Willows can grow fast enough to take up a lot of nitrates and phosphates from the soil moisture. As the plants are not grown for food, they can be irrigated with contaminated water, or fertilised using liquid bio-solids (eg sewage sludge). Willows are being used in cleaning waste water from municipal treatment works and leachate from landfill sites, and for bio-remediation of contaminated land. In experiments in the Netherlands, sludge from canal dredging operations has been pumped onto willow plantations.

Willow leaves falling on the soil tend to counteract acidification (in contrast to those of pine or spruce).

Planning Permission is likely to be needed for all except the very smallest energy conversion facilities. Planning procedures vary from one country to another, but authorities are generally interested in:

- emissions to the atmosphere (dust, smoke, odours, gases) from the conversion equipment or associated biomass storage;
- emissions to watercourses, drains and sewers;
- effects of traffic on the local road network, bridges, etc;
- noise from energy conversion, and from traffic carrying the biomass;
- visual impact of the energy conversion facilities;
- possible effects on areas designated for their ecological importance;
- effect on buildings or designed landscapes of historical interest;
- interference with archaeological remains;
- implications for future uses of the land.

Developers need to study any strategic planning policy documents (it may be futile to propose a scheme that would conflict with an existing Local Plan or Regional Plan) and provide full information on the benefits to the environment, the local economy, etc. Planning procedures could take a long time if the authorities are unfamiliar with some of these issues.

It is almost always best to discuss the proposed developments openly with planning authorities and local inhabitants at an early stage. Objections to the development are less likely if it is clear that benefits will be spread throughout the community. Technical aspects of the plans should be flexible in case planning authorities demand changes.
8 Economics

Growing willow for energy needs government support while the industry is developed.
There are opportunities to reduce costs substantially through technical improvements.

Can willow compete with other energy sources?

Electricity. Willow may only become competitive for electricity production if prices reflect the environmental benefits, and the full environmental costs of fossil fuel or nuclear power stations (pollution control, decommissioning, etc) are taken into account. Government support will be needed while the willow energy industry develops.

Combined-heat-and-power (CHP) can help to make a willow energy scheme more viable, but it is important to remember that heat is generally sold at much lower prices than an equivalent quantity of electricity.

Heat. Wood fuels used for on-site heating can often compete with fossil fuels, particularly in rural areas where wood is available nearby. Equipment for converting wood into heat is relatively cheap and simple. Control systems rarely need to be very sophisticated – hot water tanks provide temporary energy storage, and it is easy to incorporate a standby heat source (coal, oil, gas, electricity) for use when the wood-fuelled system is out of action for maintenance purposes, etc.

Situations where small scale heating and CHP schemes may be viable include:

- schools
- prisons
- industrial estates
- sawmills
- hospitals
- country hotels
- farms
- cold stores

In most instances, willow is likely to be supplemented by other wood fuels, such as forestry residue, rather than being the sole energy source.

Support for environmental benefits

“Green” tariffs. Substantial numbers of customers are already willing to pay an increased price for energy from renewable resources.

- Individuals may do so because of a personal concern for the environment.
- A “green” image is important in some types of business. For example, retailers of timber products are very conscious of the need for sustainable forestry systems.
- Many quality assurance schemes already require businesses to carry out an audit of energy use. In future these schemes may be extended to encourage use of renewable energy.

“Green” taxation. Most countries already impose taxes on use of fossil fuels, and many are devising methods for relating taxes to the amounts of greenhouse gases produced. Arrangements are being developed whereby “carbon credits” can be traded between companies and/or between countries.

Payment for bio-remediation. “The polluter pays” has become an established principle. Industries and public utilities that need to clean up waste water, sewage sludge or landfill leachate may be prepared to pay willow growers for the privilege of using their land, and this will help to make energy production more viable.
Incentives for willow production. Many governments are willing to support energy production from willow coppice because they wish to meet obligations under international agreements (e.g., Kyoto protocol), ensure security of fuel supply; maintain employment in rural areas, and develop new industries. Support mechanisms include:

- grants assisting farmers to establish energy crops;
- annual payments for maintaining those crops, sometimes within a set-aside scheme;
- assistance with start-up costs for forming producer groups;
- long term contracts to purchase energy, sometimes at enhanced prices.

A balance of support mechanisms is likely to be most effective. Support based entirely on planting grants could lead to large areas of willow being grown on the very poorest land, with little attention paid to management of the crops. At the other extreme, a support system that relied on supplementing the price of willow fuel would encourage farmers to plant on the best land, use higher inputs of fertilisers and pesticides, and thereby lose some of the environmental benefits of willow coppice.

Is willow an attractive crop for the farmer?

A farmer can supply willow as a bulk commodity to a power station (or to a biomass fuel trader), or process the willow and sell an added value product (usually electricity). Producing the bulk commodity uses the farmer’s skills and assets (land, machinery, etc) in the conventional way. The potential income is much greater from selling electricity, but the levels of investment, management and risk are also greater.

Growing willow requires a high initial investment (land preparation, purchase of cuttings, weed control, fencing, etc) and normally no income until the end of the third year. Farmers will only plant willow if they are confident there will be a market for the fuel produced over the life of the crop.

Opportunities to reduce costs

Choice of land. Yield depends on the site and the grower's management skills. Some commercial plantations have yielded only 7 - 8 tonnes of dry matter per hectare per year, but there is potential for increased production from new varieties and husbandry techniques.

In the past, willow was often grown on the poor quality land, but some farmers may decide to use more fertile land. Costs for soil preparation, weed control and planting material are the same on poor land as on the best land, and these up-front payments are very significant for a crop that may remain in production for 25 years.

Plant breeding developments are introducing new varieties that offer:

- better resistance to diseases and pests;
- easier harvesting, because the stems are erect.

Fencing costs are likely to fall if the technique of ploughing in rabbit netting is widely adopted, or if new materials (e.g., posts made from recycled plastics) prove satisfactory.

Planting techniques under development offer opportunities to reduce costs.

Harvesting and transport. Costs for baling or bundling are likely to become more competitive with cut-and-chip methods, as machines are developed.
**Energy from Willow**

**Storage and drying.** It should be possible to reduce losses during storage of wet chips, if cheaper drying systems or airtight storage methods can be developed. Alternatively, storage losses could be minimised if satisfactory machines for bundling long material are perfected.

**Post-harvest losses.** Improved handling and storage techniques should minimise post-harvest losses. These are important because the total quantity of crop grown must be sufficient to allow for loss of dry matter at any stage (e.g., material missed by the harvester header, spilt in the field or from a transport vehicle, not picked up cleanly from an intermediate store, or lost due to respiration/rotting in storage). Material lost at a late stage in the supply chain has already incurred considerable costs.

**Energy conversion.** Gasification and pyrolysis technologies are still being developed, and costs are likely to fall as more systems are installed.

**Financing of projects.** As more experience is gained, crop yields and production of energy will become more predictable, and the costs and returns will be better understood. If the risks are well understood, it should become easier to obtain financial backing for a project.
9 Information sources

Journals

Biomass & Bioenergy Pergamon
Renewable Energy Elsevier

Books


Advisory publications


Information organisations with internet sites

European Biomass Association (AEBIOM) http://www.ecop.ucl.ac.be/aebiom/
Official EC website on renewable energy sources (AGORES) http://www.agores.org/
Biomass Energy Research Association (BERA) http://www.bera1.org/
CADDET Centre for Renewable Energy http://www.caddet-re.org
Centre for Biomass Technology, Denmark http://www.videncenter.dk
COGEN Europe http://www.cogen.org
DTI's New & Renewable Energy Programme (managed by ETSU) http://www.dti.gov.uk/renewable
European Association of Renewable Energy Research Centres (EUREC) http://www.eurec.be/
European Energy Crops InterNetwork http://www.eeci.net/
European Forum for Renewable Energy Sources (EUFORES) http://eufores.org
Game Conservancy Trust, UK http://www.game-conservancy.org.uk
Greentie http://www.greentie.org
International Energy Agency (IEA) http://www.iea.org
"Phyllis" biomass database http://www.ecn.nl/phyllis/
Pyrolysis Network http://www.pyne.co.uk
Short Rotation Woody Crops Operations Working Group, USA http://www.woodycrops.org
Government departments

In most countries, the government departments concerned with willow for energy are those having responsibility for agriculture, forestry, environment, energy, rural affairs, industry and employment. These departments are normally able to provide information on:

- local recommendations for growing energy crops;
- fiscal support measures for renewable energy;
- research institutes;
- education and training establishments;
- planning regulations.

Trade associations

In many countries there are biomass trade associations that can provide information about local growing conditions, market situations, availability of equipment, government policy, legislation and regulations. Some of these associations are listed below:

Austria Biomass Association (ABA) [http://www.biomasseverband.at](http://www.biomasseverband.at)
Belgian Biomass Association (BELBIOM) [http://www.cragx.fgov.be/belbiom](http://www.cragx.fgov.be/belbiom)
British Biogen [http://www.britishbiogen.co.uk](http://www.britishbiogen.co.uk)
Bulgarian Biomass Association (BBA) [http://www.au-plovdiv.bg](http://www.au-plovdiv.bg)
Danish Biomass Association (DANBIO) [http://www.biogasdk.d](http://www.biogasdk.dk)
Estonia Biofuels Association (EBU) [http://www.af.se/ens/english/rec](http://www.af.se/ens/english/rec)
Finnish Bioenergy Association (FINBIO) [http://www.finbioenergy.fi/index_english.html](http://www.finbioenergy.fi/index_english.html)
Italian Biomass Association (ITABIA) [http://www.energ.polimi.it/ITABIA/](http://www.energ.polimi.it/ITABIA/)
Irish Bioenergy Association (IrBEA) [http://homepage.eircom.net/~tippenergy살/IrBEA](http://homepage.eircom.net/~tippenergy/IrBEA)
Netherlands Bio-energy Association (NL-BEA) [http://www.xs4all.nl/~pbe](http://www.xs4all.nl/~pbe)
Norwegian Bioenergy Association (NoBIO) [http://www.nobio.no](http://www.nobio.no)
Slovak Association for Biomass (SK-BIOM) [http://www.skbiom.sk/](http://www.skbiom.sk/)
Swedish Bioenergy Association (SVEBIO) [http://www.svebio.se](http://www.svebio.se)
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The Scottish Agricultural College (SAC)
Environment Division, Bush Estate, Penicuik, EH26 0PH, UK

tel: +44 131 535 3001
fax: +44 131 535 3031
internet: http://www.sac.ac.uk

Swedish University of Agricultural Sciences (SLU)
Department of Short Rotation Forestry, PO Box 7016, SE-750 07, Uppsala, Sweden

tel: +46 18 671 000
fax: +46 18 673 440
internet: http://www.slu.se

Netherlands Energy Research Foundation (ECN)
Biomass Department, PO Box 1, 1755 ZG Petten, The Netherlands

tel: +31 224 564722
fax: +31 224 563487
internet: http://www.ecn.nl